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Advances in Insecticide Tools and Tactics for Protecting Conifers from Bark Beetle Attack in the Western United States

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Additional information is available at the end of the chapter

1. Introduction

Bark beetles (Coleoptera: Curculionidae, Scolytinae), a large and diverse group of insects consisting of ~550 species in North America and >6,000 species worldwide, are primary disturbance agents in coniferous forests of the western U.S. Population levels of a number of species (<1%) oscillate periodically, often reaching densities that result in extensive tree mortality when favorable climatic (e.g., droughts) and forest conditions (e.g., dense stands of susceptible hosts) coincide (Table 1). The genera *Dendroctonus*, *Ips* and *Scolytus* are well recognized in this regard. In recent decades, billions of conifers across millions of hectares have been killed by native bark beetles in forests ranging from Alaska to New Mexico, and several recent outbreaks are considered the largest and most severe in recorded history.

Host selection and colonization behavior by bark beetles are complex processes. Following initial attacks and subsequent mating, adults lay eggs in the phloem and larvae excavate feeding tunnels in this tissue and/or the outer bark. Depending on the bark beetle species and the location and severity of feeding, among other factors, this process may result in mortality of the host tree. Top-kill and/or branch mortality are not uncommon. Following pupation, adult beetles of the next generation tunnel outward through the bark and initiate flight in search of new hosts. The lifecycle may be repeated once every several years or several times a year depending on the bark beetle species, geographic location and associated climatic conditions. Extensive levels of tree mortality may result in host replacement by other tree species and plant associations, and may impact timber and fiber production, water

quality and quantity, fish and wildlife populations, aesthetics, recreation, grazing capacity, real estate values, biodiversity, carbon storage, endangered species and cultural resources.

Common name	Scientific name	Primary host(s)
Arizona fivespined ips	*Ips lecontei*	*Pinus ponderosa*
California fivespined ips	*I. paraconfusus*	*P. contorta, P. jeffreyi, P. lambertiana, P. ponderosa*
Douglas-fir beetle	*Dendroctonus pseudotsugae*	*Pseudotsuga menziesii*
eastern larch beetle	*D. simplex*	*Larix laricina*
fir engraver	*Scolytus ventralis*	*Abies concolor, A. grandis, A. magnifica*
Jeffrey pine beetle	*D. jeffreyi*	*P. jeffreyi*
mountain pine beetle*	*D. ponderosae*	*P. albicaulis, P. contorta, P. flexilis, P. lambertiana, P. monticola, P. ponderosa*
northern spruce engraver	*I. perturbatus*	*Picea glauca, Pi. x lutzii*
pine engraver	*I. pini*	*P. contorta, P. jeffreyi, P. lambertiana*
pinyon ips	*I. confusus*	*P. edulis, P. monophylla*
roundheaded pine beetle	*D. adjunctus*	*P. arizonica, P. engelmannii, P. flexilis, P. leiophylla, P. ponderosa, P. strobiformis*
southern pine beetle	*D. frontalis*	*P. engelmannii, P. leiophylla, P. ponderosa*
spruce beetle*	*D. rufipennis*	*Pi. engelmannii, Pi. glauca, Pi. pungens, Pi. sitchensis*
western balsam bark beetle	*Dryocoetes confusus*	*A. lasiocarpa*
western pine beetle*	*D. brevicomis*	*P. coulteri, P. ponderosa*

*Species for which preventative insecticide treatments have been well studied.

Table 1. Bark beetle species that cause significant amounts of tree mortality in coniferous forests of the western U.S.

While native bark beetles are a natural part of the ecology of forests, the economic and social impacts of outbreaks can be substantial. Several tactics are available to manage bark beetle infestations and to reduce associated levels of tree mortality. While these vary by bark beetle species, current tactics include tree removals that reduce stand density (thinning) and presumably host susceptibility [1]; sanitation harvests [1]; applications of semiochemicals (i.e., chemicals produced by one organism that elicit a response, usually behavioral, in another

organism) to protect individual trees or small-scale stands (e.g., <10 ha) [2]; and preventative applications of insecticides to individual trees. The purpose of this chapter is to synthesize information on the efficacy, residual activity, and environmental safety of insecticides commonly used to protect trees from bark beetle attack so that informed, judicious decisions can be made concerning their use.

2. Types and use of preventative applications of insecticides

Preventative applications of insecticides involve topical sprays to the tree bole (bole sprays) or systemic insecticides injected directly into the tree (tree injections) [3]. Systemic insecticides applied to the soil are generally ineffective. In an operational context, only high-value, individual trees growing in unique environments or under unique circumstances are treated. These may include trees in residential (Fig. 1), recreational (e.g., campgrounds) (Fig. 2) or administrative sites. Tree losses in these environments result in undesirable impacts such as reduced shade, screening, aesthetics, and increased fire risk. Dead trees also pose potential hazards to public safety requiring routine inspection, maintenance and eventual removal [4], and property values may be negatively impacted [5]. In addition, trees growing in progeny tests, seed orchards, or those genetically resistant to forest diseases may be considered for preventative treatments, especially if epidemic populations of bark beetles exist in the area. During large-scale outbreaks, hundreds of thousands of trees may be treated annually in the western U.S., however once an outbreak subsides (i.e., generally after one to several years) preventative treatments are often no longer necessary.

Figure 1. Tree mortality attributed to western pine beetle in San Bernardino County, California, U.S. In the wildland urban interface, tree losses pose potential hazards to public safety and costs associated with hazard tree removals can be substantial. Furthermore, property values may be significantly reduced. The value of these trees, cost of removal and loss of aesthetic value often justify the use of insecticides to protect trees from bark beetle attack during an outbreak. Photos: C.J. Fettig, Pacific Southwest Research Station, USDA Forest Service.

Figure 2. Conditions before (left) and after (right) a spruce beetle outbreak impacted the Navajo Lake Campground on the Dixie National Forest, Utah, U.S. Daily use decreased substantially due to reductions in shade, screening and aesthetics associated with mortality and removal of large diameter overstory trees. Photos: A.S. Munson, Forest Health Protection, USDA Forest Service.

Although once common, insecticides are rarely used today for direct or remedial control (i.e., subsequent treatment of previously infested trees or logs to kill developing and/or emerging brood). While remedial applications have been demonstrated to increase mortality of brood in treated hosts, there is limited evidence of any impact to adjacent levels of tree mortality. Furthermore, there are concerns about the effects of remedial treatments on non-target invertebrates, specifically natural enemy communities. Many of these species respond kairomonally to bark beetle pheromones and host volatiles, and their richness increases over time [6], suggesting that the later remedial treatments are applied the more likely non-target organisms will be negatively impacted.

3. Insecticide registrations

Insecticide sales and use in the U.S. are regulated by federal (U.S. Environmental Protection Agency, EPA) and state (e.g., California Department of Pesticide Regulation in California) agencies. Therefore, product availability and use vary by state. EPA regulates all pesticides under broad authority granted in two statutes, (1) the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) that requires all pesticides sold or distributed in the U.S. to be registered; and (2) the Federal Food, Drug and Cosmetic Act that requires EPA to set pesticide tolerances for those used in or on food. EPA may authorize limited use of unregistered pesticides or pesticides registered for other uses under certain circumstances. Under Section 5 of FIFRA, EPA may issue experimental use permits that allow for field testing of new pesticides or uses. Section 18 of FIFRA permits the unregistered use of a pesticide in a specific geographic area for a limited time if an emergency pest condition exists. Under Section 24(c) of FIFRA, states may register a new pesticide for any use, or a federally-registered product for an additional use, as long as a "special local need" is demonstrated.

A complete list of active ingredients and products used for protecting trees from bark beetle attack is beyond our scope as availability changes due to cancellations, voluntary with-

draws, non-payment of annual registration maintenance fees, and registration of new products at federal and state levels. Several studies have been published on the efficacy of various classes, active ingredients, and formulations that are no longer registered [e.g., benzene hexachloride (Lindane®)]. Therefore, we limit much of our discussion to the most commonly used and/or extensively-studied products (Fig. 3). A list of products registered for protecting trees from bark beetle attack can be obtained online from state regulatory agencies and/or cooperative extension offices, and should be consulted prior to implementing any treatment. Furthermore, all insecticides registered and sold in the U.S. must carry a label. It is a violation of federal law to use any product inconsistent with its labeling. The label contains abundant information concerning the safe and appropriate use of insecticides (e.g., signal words, first aid and precautionary statements, proper mixing, etc.). For tree protection, it is important to note whether the product is registered for ornamental and/or forest settings, and to limit applications to appropriate sites using suitable application rates.

Figure 3. The carbamate carbaryl and pyrethroids bifenthrin and permethrin are commonly used to protect trees from bark beetle attack in the western U.S. Several formulations are available and effective if properly applied. Residual activity varies with active ingredient, bark beetle species, tree species, geographic location, and associated climatic conditions. Photos: C.J. Fettig, Pacific Southwest Research Station, USDA Forest Service.

4. Experimental designs for evaluating preventative treatments

When evaluating preventative treatments one of three experimental designs is generally used. Each has its own advantages and disadvantages. Laboratory assays require trapping and/or rearing of live bark beetles for inclusion in experiments. Captured individuals are immediately transported to the laboratory, identified and sorted. Damaged (e.g., loss of any appendages), weakened, or beetles not assayed within 48 h after collection should be discarded. Generally, serial dilutions of each insecticide are prepared, and toxicity is determined in filter paper or topic assays [7]. The life-table method is used to estimate the survival probability of test subjects to different doses of each insecticide [7]. Filter paper assays more closely approximate conditions under which toxicants are encountered by bark beetles during host colonization, especially for products other than contact insecticides [7], but both methods ignore important environmental factors (e.g., temperature, humidity and sunlight) and host tree factors (e.g., architecture) that influ-

ence efficacy. However, results are rapidly obtained with limited risk and loss of scientific infrastructure compared to field studies.

A second design involves field assays in which insecticides are applied to an experimental population of ~25−35 uninfested trees [8]. Trees are often baited with a bark beetle species-specific attractant to increase beetle "pressure" and challenge the treatment following application. Efficacy is based on tree mortality and established statistical parameters [8]. This design is accepted as the standard for evaluating preventative treatments for tree protection in the western U.S., and provides a very conservative test of efficacy [9]. However, it is laborious, time-consuming (i.e., generally efficacy is observed for at least two field seasons) and expensive. Experimental trees may be lost to woodcutting or wildfire, and ≥60% of the untreated control trees must die from bark beetle attack to demonstrate that significant bark beetle pressure exists in the area or the experiment fails and results are inconclusive [8]. Some have argued that the design is perhaps too conservative as under natural conditions aggregation pheromone components would not be released for such extended periods of time as often occurs with baiting. Finally, bark beetles may initiate undesirable infestations near experimental trees as a result of baiting, which may be unacceptable under some circumstances.

The "hanging bolt" assay [10], "small-bolt" assay [11] and similar variants have received limited attention in the western U.S. Typically, insecticides are applied to individual, uninfested trees that are later harvested and cut into bolts for inclusion in laboratory and/or field experiments. Alternatively, freshly-cut bolts may be treated directly in the laboratory. Efficacy is often based on measures of attack density or gallery construction by adult beetles. Compared to [8], these methods allow for rapid acquisition of data; reduced risk of loss to scientific infrasture; and increased probability that a rigorous test will be achieved as bolts are transported to active infestations or brought into the laboratory and exposed to beetles. While these methods account for some host factors (e.g., bark architecture), others such as host defenses and environmental factors are ignored. Furthermore, the hanging bolt and small bolt assays do not provide an estimate of tree mortality, while the effectiveness of any preventative treatment is defined by reductions in tree mortality.

5. Topical applications to the tree bole

Topical applications to protect trees from bark beetle species such as western pine beetle, *Dendroctonus brevicomis* LeConte, mountain pine beetle, *D. ponderosae* Hopkins, and spruce beetle, *D. rufipennis* (Kirby), are applied with ground-based sprayers at high pressure [e.g., ≥2,241 kPa] to the tree bole. Insecticides are applied on all bole surfaces up to a height of ~10.6 to 15.2 m until runoff generally from the root collar to mid-crown (Fig. 4). For engraver beetles, *Ips* spp., that typically colonize smaller diameter hosts branches >5 cm diameter should also be treated. The amount of material (product + water) applied varies with bark and tree architecture, tree size, equipment and applicator, among other factors, but ranges from ~15 to 30 L per tree under most circumstances [12-14]. Application efficiency, the percentage of material applied that is retained on trees, ranges from ~80 to 90% [14].

Figure 4. A common method of protecting trees from bark beetle attack is to saturate all surfaces of the tree bole using a ground-based sprayer at high pressure. Photos: C.J. Fettig, Pacific Southwest Research Station, USDA Forest Service.

Bole sprays are typically applied in late spring prior to initiation of the adult flight period for the target bark beetle species. However, bole sprays require transporting sprayers and other large equipment, which can be problematic in high-elevation forests where snow drifts and poor road conditions often limit access. Additionally, many recreation sites (e.g., campgrounds) where bole sprays are frequently applied occur near intermittent or ephemeral streams that are associated with spring runoff, limiting applications in late spring due to restrictions concerning the use of no-spray buffers to protect non-target aquatic organisms. For these and other reasons, researchers are evaluating alternative timings of bole sprays and less laborious delivery methods.

5.1. Carbaryl

Carbaryl is an acetylcholinesterase inhibitor that prevents the cholinesterase enzyme from breaking down acetylcholine, increasing both the level and duration of action of the neurotransmitter acetylcholine, which leads to rapid twitching, paralysis and ultimately death. Carbaryl is considered essentially nontoxic to birds, moderately toxic to mammals, fish and amphibians, and highly toxic to honey bees, *Apis mellifera* L., and several aquatic insects [15]. However, carbaryl is reported to pose little or no threat to warm-blooded animals. Several experts report that carbaryl is still the most effective, economically-viable, and ecologically-compatible insecticide available for protecting individual trees from mortality due to bark beetle attack in the western U.S. [9,16]. Today, carbaryl (e.g., Sevin® SL and Sevin® XLR Plus, among others) is commonly used to protect trees from bark beetle attack, and is the most-extensively studied active ingredient registered for use. Failures in efficacy are rare and typically associated with inadequate coverage, improper mixing (e.g., using an alkaline water source with pH >8) [17] or inaccurate mixing resulting in solutions of reduced concentration, improper storage, and/or improper timing (e.g., applying treatments to trees already successfully attacked by bark beetles).

Mountain and western pine beetles. Several rates and formulations of carbaryl have been evaluated, and most research indicates two field seasons of protection can be expected with a single application. The effectiveness of 1.0% and 2.0% Sevimol® was demonstrated in the early 1980s [18-22]. This and other research [23-24] led to the registration of 2.0% Sevimol® as a preventative spray, which was voluntarily canceled in 2006. [22] evaluated the efficacy of 0.5%, 1.0% and 2.0% Sevimol® and Sevin® XLR and found all concentrations and formulations were effective for protecting lodgepole pine, *P. contorta* Dougl. ex Loud., from mortality due to mountain pine beetle attack for one year. The 1.0% and 2.0% rates were efficacious for two years. [9] reported 2.0% Sevin® SL protected ponderosa pine, *Pinus ponderosa* Dougl. ex Laws., from western pine beetle attack in California; ponderosa pine from mountain pine beetle attack in South Dakota; and lodgepole pine from mountain pine beetle attack in Montana (two separate studies) for two field seasons. Similar results have been obtained elsewhere [12]. Ongoing research is evaluating the efficacy of fall versus spring applications of 2.0% Sevin® SL for protecting lodgepole pine from mountain pine beetle attack in Wyoming. Both treatments provided 100% tree protection during the first field season while 93% mortality was observed in the untreated control (C.J.F. and A.S.M., unpublished data). A similar study is being conducted for mountain pine beetle in ponderosa pine in Idaho.

Southern pine beetle. Southern pine beetle, *D. frontalis* Zimmerman, occurs in a generally continuous distribution across the southern U.S., roughly coinciding with the distribution of loblolly pine, *P. taeda* L. However, southern pine beetle also occurs in portions of Arizona and New Mexico where it colonizes several pine species, and is therefore considered here. While preventative treatments have not been evaluated in western forests, carbaryl is ineffective for protecting loblolly pine from mortality due to southern pine beetle attack in the southern U.S. [25-26]. This was later linked to insecticide tolerance in southern pine beetle associated with an efficient conversion of carbaryl into metabolites, and a rapid rate of excretion [27-29]. Therefore, despite important environmental differences between the southern and western U.S., carbaryl is regarded as ineffective for preventing southern pine beetle attacks and subsequent tree mortality in the western U.S. [30].

Spruce beetle. Most research suggests that three field seasons of protection can be expected with a single application of carbaryl. In south-central Alaska, [31] reported that 1.0% and 2.0% Sevin® SL protected white spruce, *Picea glauca* (Moench) Voss, and Lutz spruce, *P. glauca* X *lutzii* Little, from attack by spruce beetle for three field seasons, despite early work indicating carbaryl was ineffective in topical assays [32]. One and 2.0% Sevimol® were effective for protecting Engelmann spruce, *P. engelmannii* Parry ex. Engelm., from spruce beetle attack for two field seasons in Utah [33], which agrees with results from [9] for 2.0% Sevin® SL. However, the two latter studies were concluded after two field seasons. In the case of [9], all Sevin® SL-treated trees were alive at the end of the study.

Red turpentine beetle. Red turpentine beetle, *D. valens* LeConte, usually colonizes the basal portions of stressed, weakened, or dead and dying trees. Therefore, the species is not considered an important source of tree mortality in the western U.S., and limited work has occurred regarding the development of tree protection tools. [34] reported that 2.0% Sevin® XLR and 4.0% Sevimol® 4 were effective for protecting ponderosa pine in California. Several for-

mulations of carbaryl are effective for protecting Monterey pine, *P. radiata* D. Don, [35], but residual activity is generally short-lived (<1 yr).

Engraver beetles. A single application of 2.0% Sevin® SL was effective for protecting single-leaf pinyon, *P. monophylla* Torr. & Frem., from mortality due to pinyon ips, *I. confusus* (Le-Conte), for two field seasons in Nevada [9]. A similar study in pinyon pine, *P. edulis* Engelm., on the Southern Ute Reservation in Colorado found 2.0% Sevin® SL was efficacious for one field season, but bark beetle pressure was insufficient the second year of the study to make definitive conclusions regarding efficacy [9]. [9] also evaluated the efficacy of 2.0% Sevin® SL for protecting ponderosa pine from pine engraver, *I. pini* (Say), but very few trees were attacked during the experiment. Approximately one year later, trees in this study were harvested and cut into bolts that were then laid on the ground in areas containing slash piles infested with pine engraver, sixspined ips, *I. calligraphus* (Germar), and Arizona five-spined ips, *I. lecontei* Swain [13]. From this and related research, the authors concluded 1.0% and 2.0% Sevin® SL were effective for protecting ponderosa pine from engraver beetle attacks for one entire flight season in Arizona. [36] reached similar conclusions for 2.0% Sevin® 80 WSP for a complex of engraver beetles, including sixspined ips, that colonize loblolly pine in the southeastern U.S.

5.2. Pyrethroids

Pyrethroids are synthesized from petroleum-based chemicals and related to the potent insecticidal properties of flowering plants in the genus *Chrysanthemum*. They are axonic poisons and cause paralysis by keeping the sodium channels open in the neuronal membranes [37]. First generation pyrethroids were developed in the 1960s, but are unstable in sunlight. By the mid-1970s, a second generation was developed (e.g., permethrin, cypermethrin and deltamethrin) that were more resistant to photodegradation, but have substantially higher mammalian toxicities. Third generation pyrethroids (e.g., bifenthrin, cyfluthrin and lambda-cyhalothrin) have even greater photostability and insecticidal activity compared to previous generations. Pyrethroids are one of the least acutely toxic insecticides to mammals, essentially nontoxic to birds, but are highly toxic to fish, amphibians and honey bees [38]. Today, permethrin (e.g., Astro® and Dragnet®, among others) and bifenthrin (e.g., Onyx™) are commonly used to protect trees from bark beetle attack, and following carbaryl are the most-extensively studied active ingredients registered for use.

Mountain and western pine beetles. Several active ingredients and formulations of pyrethroids have been evaluated as preventative treatments, and most research indicates at least one field season of protection can be expected with a single application. [8] evaluated 0.1%, 0.2% and 0.4% permethrin (Pounce®) for protecting ponderosa pine from mortality due to western pine beetle attack, and reported that 0.2% and 0.4% provided control for four months. Permethrin plus-C (Masterline®), a unique formulation containing methyl cellulose (i.e., "plus-C") thought to increase efficacy and stability by reducing photo-, chemical- and biological-degradation of the permethrin molecule, exhibits efficacy similar to that of other formulations of permethrin [12]. [39] examined several rates of esfenvalerate (Asana® XL) and cyfluthrin (Tempo® 20 WP) as preventative treatments. In California, 0.025% and 0.05%

Asana® XL protected ponderosa pine for western pine beetle attack for one field season, but not a second. In Montana, 0.006% and 0.012% Asana® XL were ineffective for protecting lodgepole pine from mountain pine beetle, but 0.025% was effective for one field season. Tempo® 20 WP applied at 0.025% provided protection of ponderosa pine from western pine beetle for one field season in Idaho, but not California [39]. Surprisingly, 0.025%, 0.05% and 0.1% Tempo® 20 WP were effective for protecting lodgepole pine from mountain pine beetle attack for two field seasons [39]. [9] evaluated 0.03%, 0.06% and 0.12% bifenthrin (Onyx™) reporting at minimum one field season of protection for mountain pine beetle in lodgepole pine and two field seasons of protection for western pine beetle in ponderosa pine. This study and related research led to the registration of 0.06% Onyx™ as a preventative spray in the mid-2000s. [40] reported 0.06% Onyx™ failed to provide three field seasons of protection for western pine beetle in ponderosa pine, confirming Onyx™ is only effective for two field seasons in that system.

Southern pine beetle. While limited research has occurred, permethrin (Astro®) appears to have longer residual activity than bifenthrin (Onyx™) at least in small-bolt assays [11].

Spruce beetle. Most research suggests that at least one field season of protection can be expected. [9] reported 0.03%, 0.06% and 0.12% bifenthrin (Onyx™) would likely provide protection for two field seasons in Utah. However, 0.025% cyfluthrin (Tempo® 2) and 0.025% and 0.05% esfenvalerate (Asana® XL) only provided one field season of protection in Utah [33]. Protection of Lutz spruce in Alaska is possible for two field seasons with a single application of 0.25% permethrin (formulation unreported) [41].

Red turpentine beetle. [35] reported 0.5% permethrin (Dragnet®) was effective for protecting Monterey pine, and that it had longer residual activity than carbaryl. [34] reported 0.1%, 0.2% and 0.4% permethrin (formulation unreported) were ineffective for protecting ponderosa pine from red turpentine beetle.

Engraver beetles. Most research suggests that at least one field season of protection can be expected with a single application; however, [9] reported 0.03%, 0.06% and 0.12% bifenthrin (Onyx™) protected single-leaf pinyon from pinyon ips for two field seasons in Nevada. A similar study on the Southern Ute Reservation in Colorado found 0.12% Onyx™ protected pinyon pine for one field season, but bark beetle pressure was insufficient the second year of the study to make conclusions regarding efficacy at that rate. Both 0.03% and 0.06% Onyx™ were ineffective [9]. [13] reported that 0.19% permethrin plus-C (Masterline®) and 0.06% bifenthrin (Onyx™) were effective for protecting ponderosa pine bolts from engraver beetle attack in Arizona. [36] reported 0.06% bifenthrin (Onyx™) significantly reduced colonization of trees by bark and woodboring beetles, including sixspined ips, in the southeastern U.S.

6. Systemic injections to the tree bole

Researchers attempting to find safer, more portable and longer-lasting alternatives to bole sprays have evaluated the effectiveness of injecting small quantities of systemic in-

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http://dx.doi.org/10.5772/54178

secticides directly into the lower bole. Early work indicated that several methods, active ingredients and formulations were ineffective [e.g., 13,42-44]. In recent years, the efficacy of phloem-mobile active ingredients injected with pressurized systems (e.g., Sidewinder® Tree Injector, Tree I.V. micro infusion® and Wedgle® Direct-Inject™) capable of maintaining >275 kPA have been evaluated for engraver beetles, mountain pine beetle, southern pine beetle, spruce beetle, and western pine beetle (Fig. 5). These systems push adequate volumes of product (i.e., generally less than several hundred ml for even large trees) into the small vesicles of the sapwood [45]. Applications take <15 minutes per tree under most circumstances. Following injection, the product is transported throughout the tree to the target tissue (i.e., the phloem where bark beetle feeding occurs). Injections can be applied at any time of year when the tree is actively translocating, but time is needed to allow for full distribution of the active ingredient within the tree prior to the tree being attacked by bark beetles. Under optimal conditions (e.g., adequate soil moisture, moderate temperatures and good overall tree health) this takes ~4 weeks [46], but may take much longer, particularly in high-elevation forests. Tree injections represent essentially closed systems that eliminate drift, and reduce non-target effects and applicator exposure, but efficacy is often less than that observed for bole sprays in high-elevation forests [40]. Significant advancements in the development of this technology have been made in recent years, but tree injections are still rarely used in comparison to bole sprays in the western U.S. With the advent of designer formulations of insecticides specific for tree injection, we suspect that tree injections will become a more common tool for protecting trees from bark beetle attack in the near future, particularly in areas where bole sprays are not practical (e.g., along property lines or within no-spray buffers).

Figure 5. Experimental injections of emamectin benzoate for protecting trees from western pine beetle attack in Calaveras County, California, U.S. (left), and mountain pine beetle attack in the Uinta-Wasatch-Cache National Forest, Utah, U.S. (right). Photos: C.J. Fettig, Pacific Southwest Research Station, USDA Forest Service (left) and D.M. Grosman, Texas A&M Forest Service (right).

6.1. Emamectin benzoate

Emamectin benzoate is a macrycyclic lactone derived from avermectin B1 (= abamectin) by fermentation of the soil actinomycete *Streptomyces avermitilis* that disrupts neurotransmitters causing irreversible paralysis. Emamectin benzoate is highly toxic to fish and honey bees, and very highly toxic to aquatic invertebrates. It is highly toxic to mammals and birds as well on an acute oral basis, but is dermally benign to mammals. In recent years, emamectin benzoate has received the most attention among systemic injections for protecting trees from bark beetle attack in the western U.S. [40].

Mountain and western pine beetles. [40] evaluated an experimental formulation of 4.0% emamectin benzoate mixed 1:1 with methanol for protecting ponderosa pine from mortality due to western pine beetle attack in California. Results of this study indicate three field seasons of protection can be expected with a single application. To our knowledge, this was the first demonstration of a successful application of a systemic insecticide for protecting individual trees from mortality due to bark beetle attack in the western U.S. This and other research led to the registration of emamectin benzoate (TREE-age™) in 2010 for protecting individual trees from bark beetle attack.

The experimental formulation of emamectin benzoate was ineffective for protecting lodgepole pine from mountain pine beetle attack in Idaho [40], which agrees with field studies conducted in British Columbia and Colorado (D.M.G., unpublished data). Site conditions such as ambient temperatures, soil temperatures and soil moistures may help explain the lack of efficacy observed in these studies as these factors may slow product uptake and translocation within trees in high-elevation forests [40]. As such, failures for protecting lodgepole pine from mountain pine beetle attack were initially attributed to inadequate distribution of the active ingredient following injections made ~5 weeks prior to trees coming under attack by mountain pine beetle [40]. The authors commented that injecting trees in the fall and/or increasing the number of injection points per tree could perhaps increase efficacy. Currently, spring and fall applications of TREE-age™ are being evaluated for protecting lodgepole pine from mortality due to mountain pine beetle attack in Utah. Results for fall treatments are very promising (Table 2).

Southern pine beetle. Several studies have evaluated the efficacy of emamectin benzoate for protecting loblolly pine from mortality due to southern pine beetle attack in the southern U.S. [47, D.G.M., unpublished data]. Most have demonstrated a reduction in tree mortality, but few trees were attacked in the untreated controls, presumable due to low population levels.

Spruce beetle. An experimental formulation of 4.0% emamectin benzoate injected in late August was ineffective for protecting Engelmann spruce from mortality due to spruce beetle attack in Utah [40]. However, the commercial formulation TREE-age™ has yet to be evaluated. Studies are planned to evaluate alternative timings of injection of TREE-age™ (i.e., early summer versus late summer) and the number and position of the injection ports in trees, both of which are thought to influence efficacy [40].

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http://dx.doi.org/10.5772/54178

Engraver beetles. Several studies have reported that emamectin benzoate is effective for preventing engraver beetle attacks, including sixspined ips, for at least two years in Texas [46, D.M.G., unpublished data].

Treatment[a]	Rate[b] (/2.54 cm dbh)	Percent mortality[c]
Spring injection	10 ml	33%
Fall injection	10 ml	0%
Untreated control (yr 1)	-	80%
Untreated control (yr 2)	-	60%

[a] Injections occurred in spring (i.e., June, ~1 month prior to peak mountain pine beetle that year) and fall (i.e., September, ~10 months prior to peak mountain pine beetle flight the following year).

[b]dbh = diameter at breast height (1.37 m in height).

[c]Based on presence or absence of crown fade in September 2011. Data obtained from Fettig et al. (unpublished data).

Table 2. The effectiveness of injections of emamectin benzoate (TREE-age™) into the lower bole of lodgepole pine for reducing levels of tree mortality due to mountain pine beetle attack, Uinta-Wasatch-Cache National Forest, Utah, U.S., 2009-2011.

6.2. Abamectin

Abamectin (= avermectin B1) is a natural fermentation product of the soil actinomycete *Streptomyces a. vermitilis.* Like emamectin benzoate, abamectin acts on insects by interfering with neural and neuromuscular transmission. Abamectin is relatively non-toxic to birds, but highly toxic to fish, aquatic invertebrates and honeybees. Most formulated products are of low toxicity to mammals. Ongoing studies indicate Abacide™ 2 is effective for protecting lodgepole pine from mortality due to mountain pine beetle attack in Utah for at least one field season (C.J.F. et al., unpublished data). Similarly, efficacy has been demonstrated for a complex of engraver beetles, including sixspined ips, for three field seasons in Texas (D.G.M., unpublished data). A request to add mountain pine beetle and engraver beetles to the label for Abacide™ 2 may be forthcoming.

6.3. Fipronil

Fipronil is a phenyl pyrazole that disrupts the insect central nervous system by blocking the passage of chloride ions through the gamma-aminobutyric acid (GABA) receptor and glutamate-gated chloride channels. This results in hyperexcitation of contaminated nerves and muscles and ultimately death. Fipronil is of low to moderate toxicity to mammals, highly toxic to fish, aquatic invertebrates, honeybees and upland game birds, but is practically non-toxic to waterfowl and other bird species. Fipronil reduced levels of tree mortality due to engraver beetles, including sixspined ips, on stressed trees in Texas [46]. However, fipronil is ineffective for protecting loblolly pine from southern pine beetle [47] and Engelmann spruce from spruce beetle [40,48]. While results are inconclusive [40, 48], fipronil does not

appear effective from reducing levels of lodgepole pine mortality due to mountain pine beetle attack in Utah or ponderosa pine mortality due to western pine beetle attack in California. Thus, registration is not being pursued at this time.

7. Environmental concerns

Most data on the deposition, toxicity, and environmental fate of insecticides in western forests come from aerial applications to control tree defoliators, and therefore are of limited applicability to bole sprays or tree injections used to protect trees from bark beetle attack. [49] studied the effects of lindane, chlorpyrifos and carbaryl on a California pine forest soil arthropod community by spraying normal levels of insecticide, and levels five times greater than would be operationally used to protect trees from bark beetle attack. The authors concluded carbaryl was least disruptive to the soil arthropod community [49]. Persistence and movement of 2.0% carbaryl within soils of wet and dry sites has been evaluated [50]. The highest concentrations of carbaryl were detected within the uppermost soil layers (upper 2.54 cm), with levels exceeding 20 ppm 90 d after application on most sites [50].

Carbaryl is relatively nontoxic to *Enoclerus lecontei* (Wolcott) [51] and *E. sphegeus* (F.) [52], and less toxic than either lindane or chlorpyrifos to *Temnochila chlorodia* (Mannerheim) [51], common predators of bark beetles in the western U.S. [32] measured the remedial efficacy of 0.25%, 0.5%, 1.0%, and 2.0% chlorpyrifos (Dursban®), fenitrothion (Sumithion®) and permethrin (Pounce®) on emerged and nonemerged predators and parasites of spruce beetle in Alaska. Two percent Pounce® had the least impact on emerged natural enemies while Dursban® and Sumithion® had the greatest impacts. In many cases, the lowest concentrations resulted in the highest mortality of emerged parasites and predators (74-94% mortality), but lowest mortality of nonemerged individuals. The authors attributed this to higher concentrations resulting in prolong emergence [32]. Mortality of nonmerged parasites and predators was <45% for all active ingredients and concentrations, except 2.0% chlorpyrifos [32].

Werner and Hilgert [53] monitored permethrin levels in a freshwater stream adjacent to Lutz spruce that were treated with 0.5% permethrin (Pounce®) to prevent spruce beetle attack. Treatments occurred within 5 m of the stream. Maximum residue levels ranged from 0.05 ± 0.01 ppb 5 h after treatment to 0.14 ± 0.03 ppb 8-11 h after treatment, declining to 0.02 ± 0.01 ppb after 14 h. Levels of permethrin in standing pools near the stream were 0.01 ± 0.01 ppb. Numbers of drifting aquatic invertebrates increased two-fold during treatment and four-fold 3 h after treatment and declined to background levels within 9 h. Trout fry, periphyton and benthic invertebrates were unaffected [53].

Two studies have been published on the amount of drift resulting from carbaryl applications to protect trees from bark beetle attack. In the early 1980s, [54] used spectrophotofluorometry to analyze ground deposition from the base of the ponderosa pine to 12 m from the bole in California. In a more recent study, [14] used high performance liquid chromatography (HPLC) to evaluate ground deposition occurring at four distances from the tree bole (7.6, 15.2, 22.9 and 38.1 m) during conventional spray applications for protecting individual

lodgepole pine from mountain pine beetle attack, and Engelmann spruce from spruce beetle attack. Despite substantial differences in these methods (i.e., spectrophotofluorometry limits detection of finer particle sizes that are accounted for with HPLC), they yielded some similar results. For example, [14] reported application efficiencies of 80.9% to 87.2%, while [54] reported values of >80%. Furthermore, [14] found no significant difference in the amount of drift occurring between lodgepole pine and Engelmann spruce at any distance from the tree bole despite differences in application rate and pressure, while [54] reported drift was similar between two methods applied at 276 kPa and 2930 kPa. However, [14] reported higher levels of ground deposition further away from the tree bole, which is expected given use of HPLC, a more sensitive method of detection.
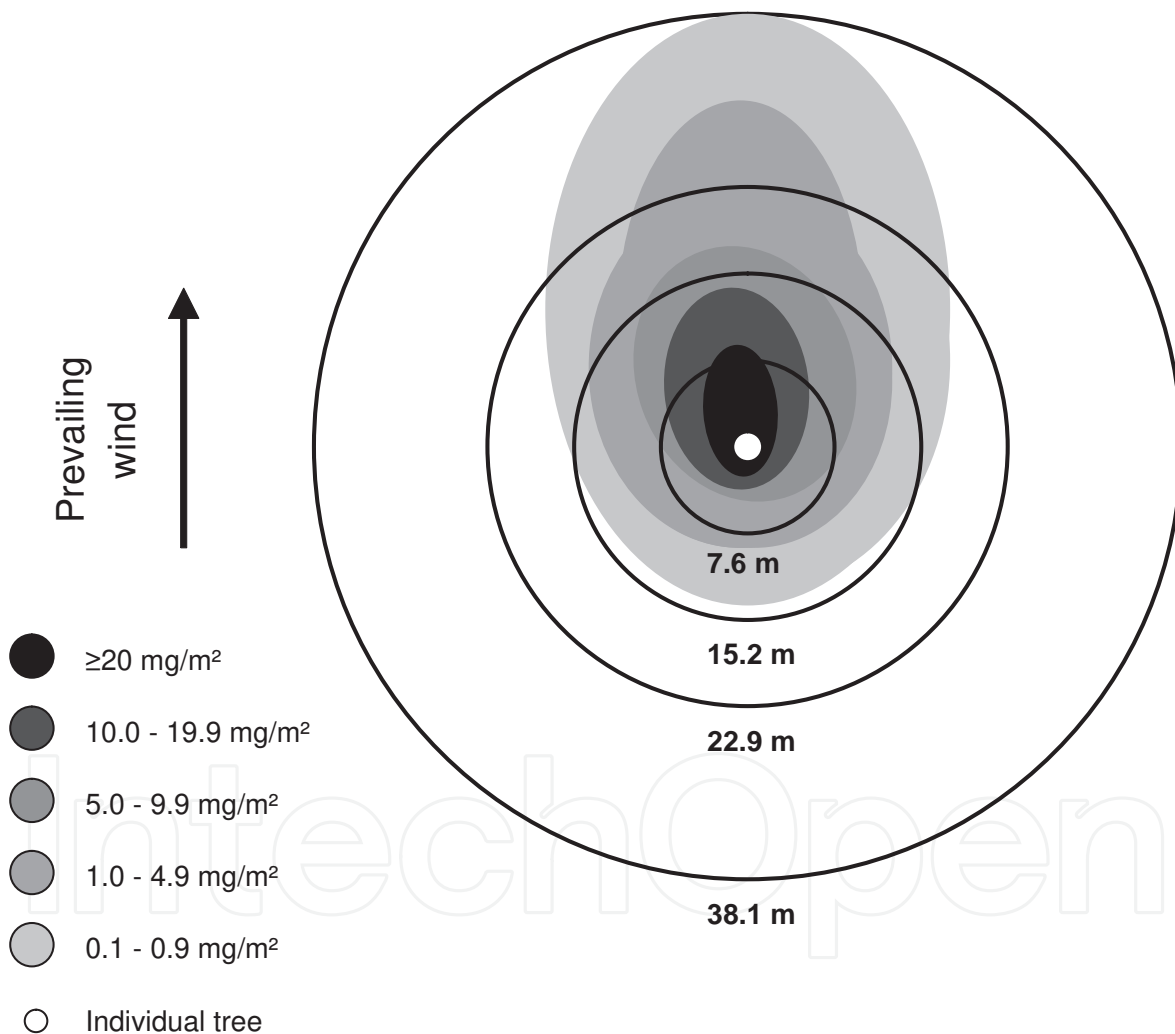

Prevailing wind

- ≥20 mg/m²
- 10.0 - 19.9 mg/m²
- 5.0 - 9.9 mg/m²
- 1.0 - 4.9 mg/m²
- 0.1 - 0.9 mg/m²
- ○ Individual tree

7.6 m
15.2 m
22.9 m
38.1 m

Figure 6. Average drift following experimental applications of carbaryl to protect trees from bark beetle attack, Uinta-Wasatch-Cache National Forest, Utah, U.S. Data obtained from Fettig et al. (2008). Wind speed was correlated with drift up to 22.9 m from the tree bole, and direction largely influenced the direction of prevailing drift. For example, while deposition is detected at 38.1 m on the leeward side of treated trees (maximum wind speeds averaged 3.5 km/h), drift is undetectable less than half that distance on the windward side. Less drift is expected in dense forest stands due to reduced wind speeds and interception by foliage. Studies show no-spray buffers will ensure that adjacent aquatic and terrestrial environments are protected from negative impacts.

Fettig et al. [14] reported mean deposition values from 0.04 ± 0.02 mg carbaryl/m^2 at 38.1 m to 13.30 ± 2.54 mg carbaryl/m^2 at 7.6 m. Overall, distance from the tree bole significantly affected the amount of deposition. Deposition was greatest 7.6 m from the tree bole and declined quickly thereafter. Approximately 97% of total spray deposition occurred within 15.2 m of the tree bole (Fig. 6). To evaluate the potential risk to aquatic environments, the authors converted mean deposition to mean concentration assuming a water depth of 0.3 m selected to represent the average size of lotic systems, primarily small mountain streams, adjacent to many recreational sites where bole sprays are often applied [14]. No adjustments were made for the degradation of carbaryl by hydrolysis, which is rapid in streams or for dilution by natural flow. Comparisons were made with published toxicology data available for select aquatic organisms. No-spray buffers of 7.6 m are sufficient to protect freshwater fish, amphibians, crustaceans, bivalves and most aquatic insects. In laboratory studies, carbaryl was found to be highly toxic to stoneflies (Plecoptera) and mayflies (Ephemeroptera), which are widely distributed and important food sources for freshwater fishes, but negative impacts in field populations are often short-lived and undetectable several hours after contamination [55]. No-spray buffers >22.9 m appear sufficient to protect the most sensitive aquatic insects such as stoneflies.

An advantage of tree injections is that they can be used on environmentally-sensitive sites as these treatments represent an essentially closed system and therefore little or no contamination occurs outside of the tree. However, following injection residues move within the tree and are frequently detected in the foliage [e.g., 44,56-57], which could pose a risk to decomposers and other soil fauna when needles senesce. This has been shown for imidacloprid in maple [57], but injections of emamectin benzoate in pines appear of little risk. For example, [56] reported emamectin benzoate was not detected in the roots or the surrounding soil, but was present at 0.011–0.025 µg/g in freshly fallen pine needles. However, levels gradually declined to below detectable thresholds after 2 months [56].

8. Conclusions

The results of the many studies presented in this chapter indicate that preventative applications of insecticides are a viable option for protecting individual trees from mortality due to bark beetle attack. Bole sprays of bifenthrin, carbaryl and permethrin are most commonly used. Several formulations are available and effective if properly applied. Residual activity varies with active ingredient, bark beetle species, tree species and associated climatic conditions, but generally one to three years of protection can be expected with a single application. Recent advances in methods and formulations for individual tree injection are promising, and further research and development is ongoing. We expect the use of tree injections to increase in the future. In general, preventative applications of insecticides pose little threat to adjacent environments, and few negative impacts have been observed. We hope that forest health professionals and other resource managers use this publication and other reports to make informed, judicious decisions concerning the appropriate use of preventative treatments to protect trees from mortality due to bark beetle attack. Additional

technical assistance in the U.S. can be obtained from Forest Health Protection (USDA Forest Service) entomologists (www.fs.fed.us/foresthealth/), state forest entomologists, and county extension agents (www.csrees.usda.gov/Extension/). We encourage use of these resources before applying any insecticides to protect trees from bark beetle attack.

Acknowledgements

This publication concerns pesticides. It does not contain recommendations for their use, nor does it imply that the uses discussed here have been registered. All uses of pesticides in the United States must be registered by appropriate State and/or Federal agencies. CAUTION: Pesticides can be injurious to humans, domestic animals, desirable plants, and fish or other wildlife—if they are not handled or applied properly. Follow recommended practices for the disposal of surplus pesticides and their containers.

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